Forecasting Optical Turbulence from Mesoscale Numerical Weather Prediction Models

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Abstract

In support of development of the Airborne Laser's (ABL) Atmospheric Decision Aid (ADA) and with the help of the ABL Challenge Project II, the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/VS) at Hanscom AFB is working on developing techniques to forecast optical turbulence from mesoscale numerical weather prediction models. The mesoscale models are used to forecast fields of horizontal wind, temperature, moisture, and pressure. The three-dimensional forecast fields are discrete grid points that represent the volumetric mean of each of these variables at each grid point location. From there, an algorithm that parameterizes the relationship between the mean fields and the sub-grid scale optical turbulence is executed to diagnose the refractive index structure constant, C_n^2. AFRL/VS has developed several parameterizations for C_n^2, including the one currently used in the ABL's ADA. AFRL/VS is continuing to work on improving the parameterizations and validate them with C_n^2 measurements collected from balloon-borne thermosondes. The mesoscale weather model that is coupled with the C_n^2 parameterizations is the fully scalable Fifth Generation National Center for Atmospheric Research/Penn State University Mesoscale Model (MM5; the Air Force's current operational model). While the results do not achieve the level of accuracy necessary for laser performance prediction, the Dewan model does show some skill in bounding the upper limit of optical turbulence that can be expected at a particular time.

1. Introduction

The Airborne Laser (ABL) Systems Program Office is currently developing a prototype Atmospheric Decision Aid (ADA) to quantify optical turbulence and cloud locations affecting the ABL. As part of the ABL Challenge Project II, AFRL/VS is performing numerical weather prediction (NWP) runs combined with optical turbulence parameterizations to assess the current ability to forecast optical turbulence at meso-scales (horizontal grid spacing ~ 10 km) in a season and at a location where ABL tests may be carried out. Vandenberg AFB, CA during the Fall season is just such a prospective season and location. Data from thermosondes measuring the refractive index structure constant, C_n^2, collected during the 2001 Vandenberg fall campaign were used to investigate the performance of three optical turbulence forecasting techniques. The optical turbulence forecast techniques evaluated included the Dewan (Dewan et al. 1993) and the CLEAR1 (Beland 1993) models, as well as a new parameterization (HMNSP99) that is described below.

2. Methodology

Currently mesoscale optical turbulence forecasting requires a two-stage approach. A flow chart illustrating this approach is shown in Fig. 1. First, a NWP mesoscale model is used to forecast fields of horizontal wind (u, v), temperature (T), water vapor (q), and pressure (P). The three-dimensional forecast fields are discrete grid points that represent the volumetric mean of each of these variables at each grid point location. Second, an algorithm that parameterizes the relationship between the mean fields and the sub-grid scale optical turbulence is executed to diagnose C_n^2. The current concept for the ABL ADA is to use mesoscale model output from the Air Force Weather Agency's (AFWA) operational NWP mesoscale model runs and run the optical turbulence parameterization locally. The specific NWP mesoscale model and optical turbulence parameterizations used in this report are described below.

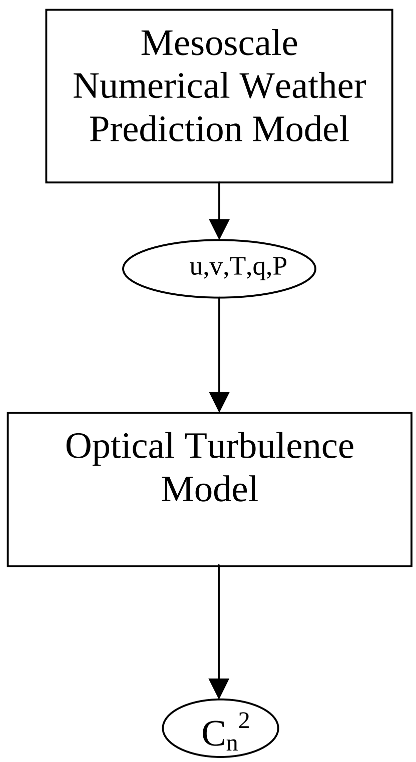

Fig. 1. Flow chart depicting two-stage approach to forecasting optical turbulence.

Table 1. Attributes of the MM5 configuration used in this study.

# of vertical levels	80
Inner-grid convective parameterization	None
PBL parameterization	MRF (Hong and Pan 1996)
Term for computation of thermal advection	Potential Temperature

2.1. Mesoscale Model

For the Dewan and HMNSP99 optical turbulence parameterizations, model forecast data from the latest version of the Fifth Generation National Center for Atmospheric Research – Penn State University Mesoscale Model (MM5, version 3; Grell et al. 1995) was used as input. This version of MM5 has been optimized for distributed memory, multiple processor machines such as the IBM SP series and scales efficiently (Michalakes, 2000). For each day of thermosonde and rawinsonde balloon flights, MM5 was run in the configuration shown in Table 1. The vertical spacing of the 80 levels used in the model was such that in addition to close spacing within the planetary boundary layer, there was approximately 300 m vertical spacing from 5 to 20 km above mean sea level (MSL). The 300 m vertical spacing was chosen because the Dewan, and HMNSP99 optical turbulence parameterizations are based on statistical relationships developed using data at that resolution.

The selection of convective and PBL parameterizations for the set of MM5 runs was made to mimic the MM5 setup used at AFWA. The selection of potential temperature as the variable to use for thermal advection was done based on arguments and tests carried out by Hsu (1997). Hsu argues that using potential temperature ensures consistency with pressure and temperature in the advection equations and results in improved depiction of mountain waves, a possible source of optical turbulence. All MM5 runs used 1º horizontal resolution data from the National Center for Environmental Prediction Aviation (AVN) Analyses and Model to provide a first guess for the standard MM5 objective analysis of upper-air and surface observations (Cressman, 1959). In addition, AVN forecasts were used to update the lateral boundary conditions of the outermost nest of MM5 during the model's integration. For all the runs, MM5 was set up to run non-hydrostatically, in triple-nested form with the attributes of each nest shown in Table 2. The horizontal domain of each grid is depicted in Fig. 2. The grid locations were chosen so that all of the comparisons with observed balloon-borne data occurred within the innermost grid. The model top was defined as 10 mb.

Table 2. Attributes of the MM5 grids used in the study.

Nest	1	2	3
Horizontal grid spacing (km)	45	15	5
Time step length (s)	90	30	10
Horizontal Domain Size (# gridpoints)	91 x 91	109 x 109	151 x 151

The Dewan and the HMNSP99 parameterizations each use different relationships for the troposphere and stratosphere. Therefore, an important part of the optical turbulence calculation is the identification of the tropopause. This is accomplished by finding for each vertical column in the NWP model 3-D grid, the height above 5000 m at which dT/dz exceeds –2.8 K km^{-1} for a depth of at least 1 km (Roe and Jasperson, 1980). That height is then assumed to be the height of the tropopause.

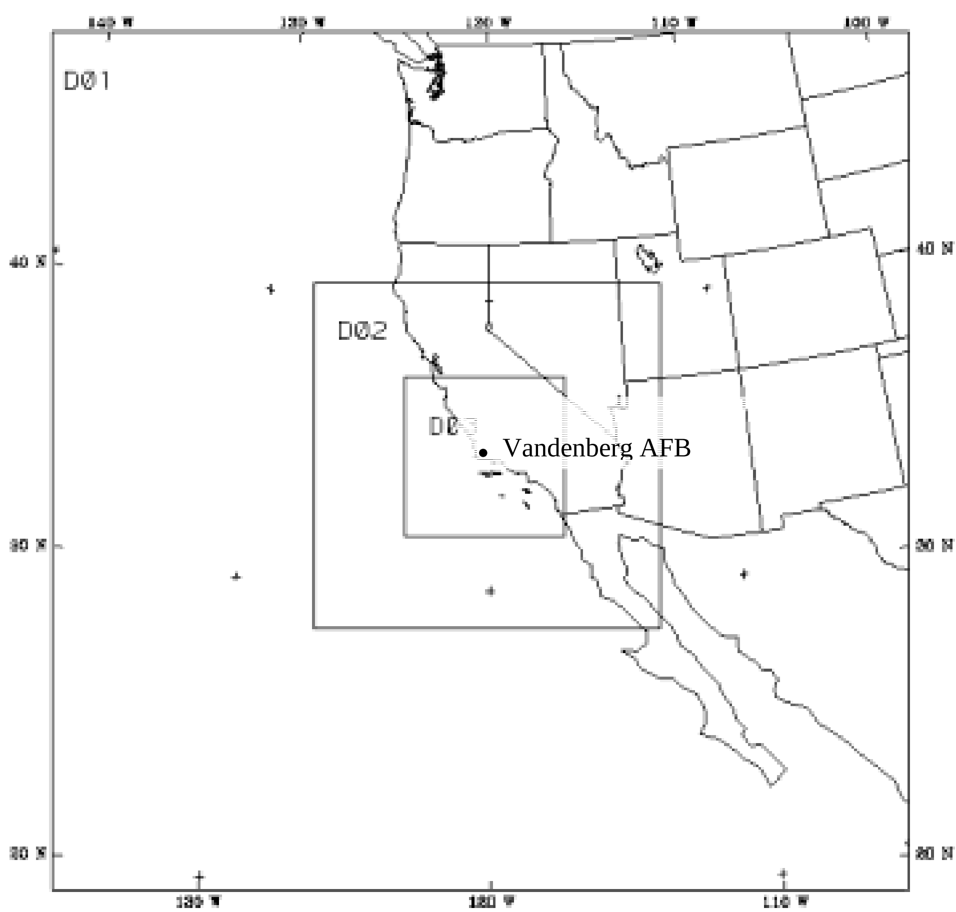

Fig. 2. Domains covered by the three MM5 grids used in this study.

2.2. Optical Turbulence Parameterizations

2.2.1 Dewan

The Dewan optical turbulence parameterization (Dewan et al. 1993) was developed to convert standard rawinsonde data into C_n^2 profiles. The Dewan parameterization uses the Tatarski (1961) formulation for the optical index of refraction structure constant,

$$C_n^2 = 2.8\left(\frac{\left(79x10^{-6}P\right)}{T^2}\right)^2 L_o^{4/3}\left(\frac{\partial T}{\partial z}+\gamma\right)^2, \qquad (1)$$

where P is the pressure in mb, T is the temperature in K, γ is the dry adiabatic lapse rate of $9.8x10^{-3}$ K m^{-1}, and z is the height in m. All of these variables are easily obtained from mesoscale NWP models, although whether the NWP models represent these variables at sufficient resolution remains an issue. The variable $L_o^{4/3}$ is referred to by Tatarski (1961) as the outer length or the largest scale of inertial range turbulence although Beland and Brown (1988) have questioned this definition. Dewan et al. (1993) closed the Tatarski relationship for C_n^2 using statistical relationships for $L_o^{4/3}$ developed as a function of wind shear using smoke trail profiles. The relationships are:

$$L_o^{4/3} = 0.1^{4/3}x10^{(1.64+42.0xS)} \qquad \text{(Troposphere)}$$

$$L_o^{4/3} = 0.1^{4/3}x10^{(0.506+50.0xS)}, \qquad \text{(Stratosphere)} \qquad (2)$$

where L_o has the units of m and S is the magnitude of the wind shear,

$$S \equiv \left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]^{0.5}. \qquad (3)$$

Ruggiero and DeBenedictis (2000) successfully employed the Dewan parameterization coupled with MM5 to provide real-time forecasts of C_n^2 to support the Scintillometer Aircraft Test (SAT99) held in New Mexico in June of 1999. The Dewan model is the optical turbulence parameterization currently included in the ABL ADA.

2.2.2 HMNSP99

Using the thermosonde data collected at Holloman AFB, New Mexico in June of 1999, Jackson and Reynolds (unpublished manuscript) developed another formulation of $L_o^{4/3}$. From Equation 1 they solved for $L_o^{4/3}$ using the observed values of C_n^2, pressure, and temperature averaged over 300 m thick vertical layers from the thermosonde balloon flights. Using these estimated values of $L_o^{4/3}$, Jackson and Reynolds then derived linAr relationships relating $L_o^{4/3}$ to observed vertical wind shear and temperature gradient as measured in 300 m increments. The relationships for the Holloman Spring 1999 (HMNSP99) parameterization are:

$$L_o^{4/3} = 0.1^{4/3} \times 10^{\left(0.362+16.728\times S-192.347\times dT/dz\right)} \qquad \text{(Troposphere)}$$

$$L_o^{4/3} = 0.1^{4/3} \times 10^{\left(0.757+13.819\times S-57.784\times dT/dz\right)}. \qquad \text{(Stratosphere)} \qquad (4)$$

It is interesting to note that these relationships show considerably less dependence on the vertical wind shear than does the Dewan parameterization.

2.2.3 CLEAR1

The CLEAR1 parameterization (Beland 1993) was also used in the comparison. Unlike the other parameterizations in this study, the CLEAR1 C_n^2 profile is a function of height only and does not need any meteorological input. The CLEAR1 parameterization was derived by statistically fitting a vertical profile though C_n^2 measurements collected during September of 1984 in New Mexico. The CLEAR1 relationships are:

$$\log_{10}\left(C_n^2\right) = A + Bz + Cz^2 \qquad 1.23 \le z \le 2.13 \qquad (5)$$

where A = -10.7025, B = -4.3502, and C = 0.8141,

$$\log_{10}\left(C_n^2\right) = A + Bz + Cz^2 \qquad 2.13 < z \le 10.34 \qquad (6)$$

where A = -16.2897, B = 0.0335, and C = -0.0134, and

$$\log_{10}\left(C_n^2\right) = A + Bz + Cz^2 + De^{-0.5\left(\frac{z-E}{F}\right)^2} \qquad 10.34 < z \le 30.00 \qquad (7)$$

where A = -17.0577, B = -0.0449, C = -0.0005, D = 0.6181, E = 15.5617, and F = 3.4666. For the CLEAR1 parameterization, z is the height above the ground in km. Over the years CLEAR1 has become analogous to the standard atmosphere and is routinely used for normalizing optical performance properties based on C_n^2.

2.3. Evaluation Procedure

2.3.1 Validation Data

Ground truth in the optical turbulence prediction validation was C_n^2 measurements collected by thermosondes during the Vandenberg Fall 2001 measurement campaign. The principle of the thermosonde is described by Brown et al. (1982). The thermosonde makes simultaneous precise measurements of temperature at two locations separated by a horizontal distance of 1 m. The theory of how C_n^2 is

Table 3. Model forecast runs and balloon observations used in the study.

Model Run #	Model Initialization Time	Balloon #	Balloon Launch Time
1	18-Oct-01 1200 UTC	002	19-Oct-01 0332 UTC
		003	19-Oct-01 0508 UTC
2	19-Oct-01 1200 UTC	004	19-Oct-01 2323 UTC
		005	20-Oct-01 0115 UTC
		006	20-Oct-01 0300 UTC
		007	20-Oct-01 0444 UTC
3	20-Oct-01 1200 UTC	008	20-Oct-01 2320 UTC
		010	21-Oct-01 0235 UTC
		011	21-Oct-01 0413 UTC
4	22-Oct-01 1200 UTC	012	23-Oct-01 0115 UTC
		013	23-Oct-01 0254 UTC
5	23-Oct-01 1200 UTC	015	24-Oct-01 0114 UTC
		016	24-Oct-01 0248 UTC
		017	24-Oct-01 0430 UTC
6	24-Oct-01 1200 UTC	018	25-Oct-01 0115 UTC
		019	25-Oct-01 0253 UTC
7	25-Oct-01 1200 UTC	021	25-Oct-01 0111 UTC
		022	26-Oct-01 0253 UTC

derived from the horizontal temperature difference in conjunction with the layer mean temperature and pressure is explained by Jumper and Beland (2000). The balloons carrying the thermosondes also carried a rawinsonde, which provided horizontal winds, temperature, moisture, and pressure measurements. All balloons were launched from Vandenberg AFB, California located at 34° 40' N, 120°25' W (Fig. 2).

2.3.2 MM5 Runs

Seven MM5 model runs were made corresponding to seven nights of thermosonde measurements. Each MM5 run was initialized approximately 12 hours before the first thermosonde release and was integrated for 24 hours. The times for each MM5 run and the corresponding balloon launch times are given in Table 3. Output was written to a file for every three hours of MM5 model integration.

After MM5 completed its 24 hours of integration, a post-processing program containing the optical turbulence parameterizations was run for each balloon flight. In addition to the output from the MM5 run, the postprocessor also read in a file containing the trajectory of the particular thermosonde balloon at 500 m vertical resolution. The balloon trajectories were computed using the wind information from the rawinsonde observations. The Dewan and HMNSP99 parameterizations computed C_n^2 for all of the MM5 pressure based sigma coordinate grid points for each model output time. Using the hypsometric equation, the C_n^2 values were interpolated vertically to 500 m increments altitude levels. At each three-hourly MM5 output time, a profile of C_n^2 along the balloon's trajectory was computed by spatially interpolating the gridded C_n^2 fields to the balloon's path. The final predicted C_n^2 profile along the thermosonde trajectory was computed by temporal interpolation using the C_n^2 profiles from the nearest two output times.

2.3.3 Evaluation Metrics

Study of the optical turbulence parameterizations performance was primarily accomplished by objective metrics. For the results presented here, the optical turbulence forecasts from the different techniques are compared with the thermosonde measurements at 500 m vertical increments. The high-resolution thermosonde observations were binned into 500 m layers and averaged to produce a layered mean C_n^2 value at 500 m vertical intervals. The model output was linearly interpolated to the same 500 m interval heights as the observed values. For each balloon flight a comparison was made between the thermosonde C_n^2 observations and model forecasts of C_n^2 at 500 m increments. The root-mean-squared (rms) error, bias, and correlation were calculated at each 500 m height increment for each profile between 5 and 21 km MSL for the Dewan, HMNSP99, and CLEAR1 parameterizations. The rms error used is the one defined by Panofsky and Brier (1968) as

Table 4. Parameters of the A and B sample scenarios

Scenario	EA	EB
Starting Altitude (km)	12.5	12.5
Ending Altitude (km)	17.0	25.1
Path length (km)	168.6	269.7

$$rms = \sqrt{\frac{\sum_{i=1}^{n}\left(F_i - O_i\right)^2}{n}} \tag{8}$$

where F_i is the forecast C_n^2 value and O_i is the observed C_n^2 value and n is the number of 500 m vertical levels between 5 and 21 km. The bias is defined as,

$$bias = \overline{F} - \overline{O} \; . \tag{9}$$

The correlation is defined as,

$$Corr. = \frac{\overline{(OF)} - \left(\overline{O}\right)\left(\overline{F}\right)}{\sqrt{\overline{O^2} - \left(\overline{O}\right)^2}\sqrt{\overline{F^2} - \left(\overline{F}\right)^2}} \; . \tag{10}$$

In all the results that will follow, the log of C_n^2 is used in the above statistical calculations.

For vertically integrated metrics, the Rytov variance was computed for the A and B sample scenarios (Table 4) assuming the “onion skin” model within the vertical profiles. Assuming a spherical wave, the Rytov variance is computed by

$$\sigma_\chi^2(s) = 0.56k^{7/6}\int_0^{s_n} C_n^2(s)\left(\frac{s}{s_n}\right)^{5/6}\left(s_n - s\right)^{5/6} ds \tag{11}$$

where k is the wavenumber of the light source assumed to have a wavelength of 1.315 μm, s is the distance along the beam path in m and s_n is the horizontal path length. The onion skin model assumes that the fields of C_n^2 are horizontally homogeneous and C_n^2 is only a function of height.   For the EB scenario, since the MM5 model data does not go above 21000 m, CLEAR1 values were used above that height for the forecast Rytov computations.

Table 5. Average rms and bias errors and correlation values of log C_n^2 for the C_n^2 forecast parameterizations computed between 5 and 21 km.

Parameterization	RMS	BIAS	Correlation
CLEAR1	0.287	0.534	0.537
Dewan	0.202	0.474	0.475
HMNSP99	0.202	0.435	0.542

3. Results

The rms and bias errors, and correlation values for model predicted C_n^2 compared to the observed thermosonde values from each balloon were averaged together and the results are presented in Table 5. These objective statistics were computed from the log of C_n^2 at levels between 5 and 21 km MSL. Statistically both the Dewan and HMNSP99 parameterizations based methods do better than CLEAR1 for rms and bias. Of the two parameterizations, Dewan has a slightly higher bias and HMNSP99 a slightly better correlation.

The rms errors of the Rytov variance for the A and B scenarios for the CLEAR1, Dewan, and HMNSP99 parameterizations are shown in Table 6. The HMNSP99 parameterization is slightly better than CLEAR1 in terms of rms and bias and is substantially better than Dewan, which suffers from a bias of over predicting the Rytov variance.

Table 6. Rms and bias errors and correlation values for Rytov variance calculations from the C_n^2 forecast parameterizations.

	A			B		
Parameterization	RMS	Bias	Correlation	RMS	Bias	Correlation
CLEAR1	0.023	0.330	0	0.045	0.122	0
Dewan	0.475	0.314	0.369	0.088	0.259	0.350
HMNSP99	0.005	0.002	0.309	0.028	0.053	0.490

Table 7. Number of cases where the computed Rytov variance was ± 50 % of observed using C_n^2 forecast parameterizations.

Within ± 50 % of Observed Rytov Variance				
	Scenario A		Scenario B	
Parameterization	Yes	No	Yes	No
CLEAR1	6	12	9	9
Dewan	3	15	8	10
HMNSP99	6	12	8	10

Table 7 shows for each scenario how many times each MM5-based optical turbulence parameterization and CLEAR1 was able to forecast the Rytov variance to within ± 50 % of the thermosonde-derived value. For scenario A, the HMNSP99 and CLEAR1 parameterizations were correct within ± 50% for one-third of the cases while Dewan was within these bounds for only one-sixth of the cases. For scenario B, the Dewan and HMNSP99 and parameterizations performed similarly as CLEAR1, correctly forecasting the Rytov variance within ± 50% of the observed value one-half of the time or slightly less.

Further insight into the prediction techniques can be seen by examining the profiles from individual cases. Figure 3 shows the observed profile of C_n^2 for balloon 010, launched at 0235 UTC 21 October 2001. Also plotted in the figure are the Dewan, HMNSP99, and CLEAR1 profiles of predicted C_n^2. The important feature to note here is the high level of C_n^2 between 12-13 km. The Dewan parameterization does an excellent job of predicting this layer. The Dewan parameterization's bias of overpredicting C_n^2 is also evident at other heights in the profile. However in a subjective review of all balloon flights (not shown), we observed that the Dewan parameterization, more often then not, correctly predicted layers where and when C_n^2 significantly exceeded the CLEAR1 values. Additional examination of the Rytov calculations reveal that for all 18 cases, the Dewan model either predicted the Rytov variance to ± 50% of the observed value or gave a value of the Rytov variance that exceeded the observed. Thus the Dewan parameterization does show skill in predicting an upper bound on the amount of turbulence that one could expect to encounter along a beam path.

4. Conclusions

This report presents a validation of optical turbulence parameterization performance using NWP model forecasts as input. A location, Vandenberg AFB, California and a season, fall, were chosen because of the possibility of ABL test being carried out at that location during that time of year. Optical turbulence predictions from

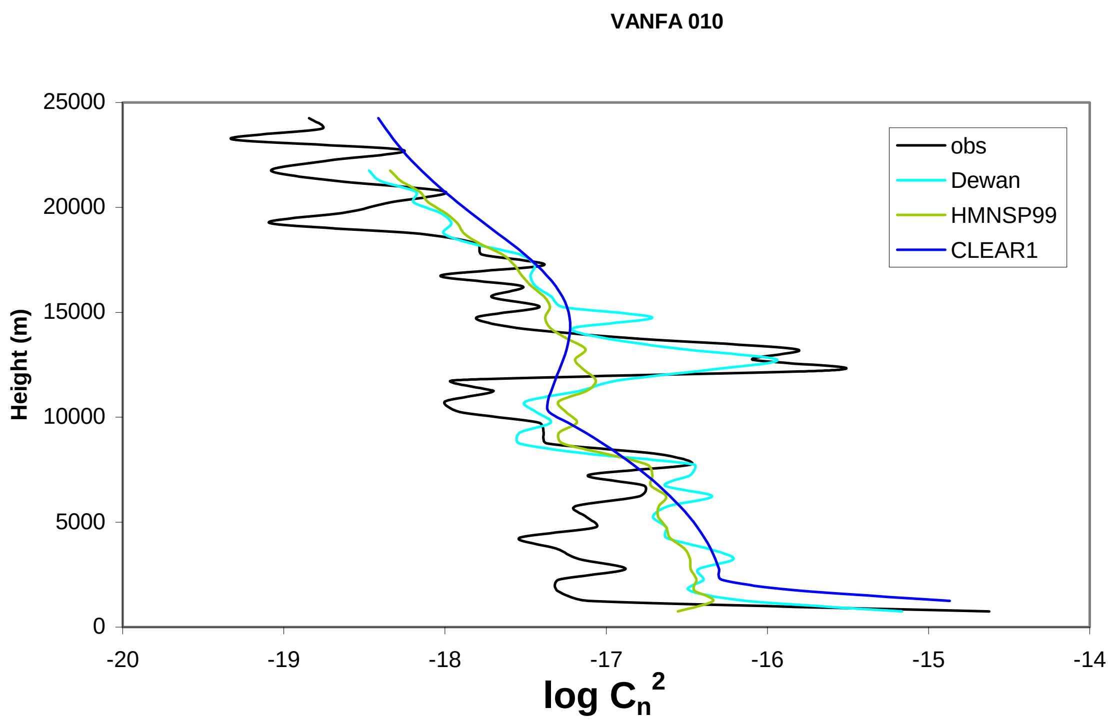

Fig. 3. Vertical profiles of log C_n^2 observed by thermosonde 010 launched on 20 October 2001 and the corresponding forecasts by C_n^2 parameterizations.

C_n^2 parameterizations were compared to balloon-borne thermosonde measurements of C_n^2. The results show that there is substantial room for improvement in the optical turbulence parameterizations. While the HMNSP99 parameterization statistically outperformed Dewan in terms of objective metrics, the Dewan parameterization has shown some forecast utility in forecasting the upper limit of optical turbulence and provide a higher detail of the structure observed in the optical turbulence profiles. For these reasons, it is recommended that the Dewan model continue to be the parameterization used in the ABL's ADA.

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